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Technical Report

The Effect of Processing Variables on Heavy Plates of 12Ni-5Cr-3Mo Steel

Applied Research Laboratory
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THE EFFECT OF PROCESSING VARIABLES ON HEAVY PLATES OF 12NI-5CR-3MO STEEL
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Approved by J. H. Gross, Division Chief

Abstract

Because rolled heavy plates of 12Ni-5Cr-3Mo steel showed markedly lower notch toughness than light plates, a series of Laboratory and production studies was initiated to determine how the properties of heavy plates might be improved by varying processing procedures.

The results of initial production studies indicated that midthickness properties of 4-inch-thick plate produced by forging slabs to plate were superior to those of plate produced by rolling. However, the toughness at the surface and quarter-thickness of the forged plate was about the same as that of the rolled plate. Laboratory studies on the effect of forging temperature and degree of reduction indicated that (1) unless very heavy drafts (over 50% reduction) are possible, forging temperatures in the range 1800 to 2000 F are advisable, and (2) for all forging temperatures, heavy drafts result in forgings with better toughness than light drafts.

Production and evaluation of a second forged plate showed that heavy-section plates with a relatively fine grain structure and improved notch toughness can be achieved by (1) using a low slab-reheating temperature (2) forging the slab to plate using heavy drafts, and (3) forging in the temperature range 1800 to 2000 F. The forged 4-inch-thick plate produced under these conditions exhibited Charpy V-notch energy absorptions of from 27 to 37 ft-lb at 80 F and a yield strength of about 184 ksi.

Introduction

One of the requirements for high-yield-strength hull steels is that the steel exhibit satisfactory properties in plates through 4 inches thick. The 12Ni-5Cr-3Mo steels are being extensively investigated as one of the types of steel that show promise, particularly in light-gage plate, for 180 to 210 ksi yield-strength hull applications.[1,2,3)*] To determine the applicability of the 12Ni-5Cr-3Mo steel in heavier plates, a 20-ton production heat was melted and plates through 4 inches thick were rolled. This report describes the generally unsatisfactory notch toughness obtained in the 4-inch-thick rolled plates and presents the results of a series of production and Laboratory studies on the initial 20-ton heat and on two additional 20-ton heats. The studies were designed to determine how the properties of heavy plates might be improved by varying processing procedures.

Materials and Experimental Work

Production Melting and Processing Procedures

Three production heats of 12Ni-5Cr-3Mo steel were used in the studies. The heats were melted at the Duquesne Works in a 20-ton basic electric furnace (heats No. X14689, X15544, and X15604) with a double-slag practice (a lime oxidizing slag and a lime-alumina reducing slag). The heats were teemed in air into 39,000-pound, 32- by 60-inch ingot molds.

After stripping, the ingots were soaked at 2300 F and rolled to the required slab sizes from the 2300 F soaking temperature. After conditioning,

*See References.

the slabs were reheated and rolled or forged to plate as described below.

Heat No. X14689 - Hot-Rolled 1/2- and 4-Inch-Thick Plates. A 55- by 6-1/2- by 85-inch slab (slab No. 59807) weighing about 8300 pounds was heated to about 2300 F, cross-rolled to a 1/2- by 72- by 360-inch plate, and air-cooled. The longitudinal (normal to the ingot axis) to transverse (parallel to the ingot axis) rolling ratio was 2.6 to 1. Following a production heat treatment that consisted of a 1-hour solution anneal at 1500 F, a water quench, a 3-hour age at 900 F, and a water quench, the plate was evaluated at the Applied Research Laboratory.

A 55- by 11- by 60-inch slab (slab No. 59804) weighing about 9900 pounds was heated to about 2300 F, cross-rolled to a 4- by 78- by 110-inch plate, and air-cooled. The longitudinal to transverse rolling ratio was 1.4 to 1. Following a production heat treatment that consisted of a 4-hour solution anneal at 1500 F, a water quench, a 3-hour age at 900 F, and a water quench, a plate section 28 by 4 by 14 inches was obtained for evaluation.

Heat No. X15544 - Forged 4-Inch-Thick Plate. A 55- by 10-3/4- by 45-inch slab (slab No. 37125) weighing about 7200 pounds was heated to 2250 F. A portion of the slab was forged normal to the ingot axis to a 4- by 45- by 67-inch plate. No attempt was made during the forging operation to control either the amount or number of forging drafts or to control the finishing temperature. The surface temperature of the finished 4-inch-thick plate was about 1500 F (optical pyrometer), and the longitudinal to transverse working ratio was 1.1 to 1.

A piece of the 4-inch-thick plate (8 by 4 by 16 inches) was heat-treated at the Laboratory (solution-annealed at 1500 F for 4 hours, water-quenched, aged at 900 F for 3 hours, and water-quenched) to provide material for evaluation.

Heat No. X15604 - Forged 4-Inch-Thick Plate. A 55- by 10-3/4- by 30-1/2-inch slab (slab No. 49668) weighing about 4800 pounds was heated to 1965 F and forged in the longitudinal direction to a 4- by 21-1/2- by 136-inch plate. Control was exercised during the forging operation to keep the number of drafts required to produce the plate thickness to no more than three while maintaining a minimum working temperature of 1800 F. The surface temperature of the finished 4-inch-thick plate was about 1700 F (optical pyrometer), and the longitudinal to transverse working ratio was 1.1 to 1.

A plate sample (6 by 4 by 12 inches) was heat-treated at the Laboratory (solution-annealed at 1500 F for 4 hours, water-quenched, aged at 900 F for 3 hours, and water-quenched) to provide material for evaluation.

Evaluation of Production 4-Inch-Thick Plate

For each specimen location (surface, quarter-thickness, and mid-thickness) and orientation (longitudinal and transverse), duplicate 0.252-inch-diameter tension-test specimens and six standard Charpy V-notch impact-test specimens were machined from the heat-treated plate material. The tension specimens were tested at room temperature and the impact specimens were tested in duplicate at three of the test temperatures 80, 32, 0, or -80 F. All specimens were oriented with the notch perpendicular to the plate surface.

Selected specimens were prepared for metallographic study and examined by light microscopy and/or electron microscopy and electron diffraction.

Laboratory Studies

The Effect of Forging Temperature and Reduction. Ten specimen blanks (4 by 4 by 4 inches) were obtained from the hot-rolled and production-heat-treated 4-inch-thick plate produced from heat No. X14689 and were homogenized at 2300 F for 2 hours and air-cooled. Thermocouples were inserted into the center of eight of the specimen blanks parallel to the final rolling direction of the 4-inch-thick plate for temperature control during the forging operation. Two specimens were then reheated and press-forged at each of the temperature combinations below to 2- or 3-inch-thick plate and air-cooled. The specimens were forged normal to the 4-inch-thick plate surface in one draft if possible.

Reheating Temperature, F	Forging Temperature, F
2300	2200
2100	2000
1900	1800
1700	1600

After cooling to room temperature, each as-forged plate sample was cut into two pieces (parallel to the final rolling direction of the 4-inch-thick plate) in preparation for subsequent heat treatment. One piece of each of the as-forged plate samples was solution-annealed at 1500 F for 1 or 4 hours, water-quenched, aged at 900 F for 3 hours, and water-quenched. At each step prior to and after the aforementioned heat treatments, metallographic specimens were examined to ascertain any changes in microstructure.

For each condition of heat treatment and specimen location (surface and midthickness), one 0.252-inch-diameter tension-test specimen and up to six standard Charpy V-notch impact-test specimens were obtained. The tension specimens were tested at room temperature and impact specimens were tested in duplicate at 80, 0, and -80 F. All specimens were longitudinally oriented (parallel to the final rolling direction of the 4-inch-thick plate) with the notch perpendicular to the plate surface.

Results and Discussion

Chemical Composition

The chemical composition of the three production steels (Duquesne heats No. X14689, X15544, and X15604) investigated are shown in Table I. The check analyses were obtained on the following plate material: (1) Heat No. X14689 from 1-inch-thick plate (plate No. 5-9806-A), (2) Heat No. X15544 from 4-inch-thick plate (plate No. 37125), and (3) Heat No. X15604 for 1-3/4-inch-thick plate (plate No. 49667). Generally, the check analyses of these steels are similar. Variations in the content of the strengthening elements, particularly molybdenum and titanium, were such that heat No. X14689 (2.86% Mo, 0.24% Ti) would be expected to exhibit the lowest strength and heat No. X15544 (3.27% Mo, 0.48% Ti) would be expected to exhibit the highest strength.

Initial Production Rolling and Forging of Heavy Plate

The mechanical properties of the rolled and heat-treated 1/2- and 4-inch-thick plates from heat No. X14689 are shown in Table II. The reduction of area and notch toughness of the 4-inch-thick plate are seen to be inferior to those of the 1/2-inch-thick plate, and the notch toughness of the 4-inch-thick plate is somewhat poorer at the quarter and midthickness than at the surface. Metallographic examination of the two plates, Figure 1, reveals that the 1/2-inch-thick plate has a fine-grained (ASTM 8), highly distorted structure and that the 4-inch-thick plate has a coarse-grained (ASTM 2 to 5-1/2) equiaxed structure that is somewhat coarser at the midthickness than at the surface. The differences in grain size were believed to be responsible for the observed differences in toughness.

Unfortunately, the grain size of 12Ni-5Cr-3Mo steels is not refined by an austenitizing treatment because the transformation from low-carbon martensite to austenite on heating from room temperature to 1500 F does not occur by the normal nucleation and growth process of carbon-containing steels, but is a simple shear transformation back to the prior austenite grain size.

Thus, a fine as-rolled austenite grain size is necessary to produce a fine-grained 12Ni-5Cr-3Mo steel.

The rolling records indicated that the finishing temperature for the 1/2-inch-thick plate was below 1500 F and that the finishing temperature for the 4-inch-thick plate was probably about 2000 F. Thus, it appeared that if the heavy plate could be subjected to sufficient work throughout the plate thickness at lower temperatures, the grain size could be significantly refined and the notch toughness improved.

Because of mill capacity limitations, it was not possible to take drafts sufficiently heavy to work the center of 4-inch-thick plates at temperatures much below 2000 F. In an attempt to attain heavy drafts at low temperatures, a second 4-inch-thick plate was produced by forging (from heat No. X15544); and as indicated earlier, the final forging of this plate was at about 1500 F. Mechanical properties of the forged plate are shown in Table III. The 4-inch-thick forged plate exhibited higher strength and more anistropy in strength and toughness than did the 4-inch-thick rolled plate, even though the longitudinal to transverse working ratio of the forged plate (1.1 to 1) was closer to 1 to 1 than that of the rolled plate (1.4 to 1). Although the notch toughness at the surface of the forged plate was about the same as that at the surface of the rolled plate, the toughness at the midthickness of the forged plate was better than that at the midthickness of the rolled plate (29 ft-lb versus 21 ft-lb Charpy V-notch energy at 80 F).

The microstructure of the as-forged plate (Figure 2) varied markedly from surface to midthickness. At the surface the grains were large and somewhat distorted, at the quarter-thickness the structure was fine and highly distorted, and at the midthickness the structure was fine and the grains were mostly equiaxed. After solution annealing and aging, unusual recrystallization and grain growth occurred, as shown in Figure 3. Very large, generally equiaxed grains were found at the surface and quarter-thickness, and small, somewhat elongated grains were found at the midthickness. Thus, it appears that this steel is susceptible to severe grain coarsening at 1500 F when a critical amount of grain distortion is present.

The above results show that the midthickness of a 4-inch-thick plate may be worked sufficiently by forging to obtain a fine-grained microstructure with notch toughness superior to that obtained by rolling. However, variations in forging temperature and degree of reduction have marked effects on the as-forged structure and on grain-growth phenomena during subsequent solution-annealing treatments. A Laboratory study was therefore initiated to more thoroughly examine the effects of forging temperature and degree of reduction on the mechanical properties and microstructure of the 12Ni-5Cr-3Mo steel.

Laboratory Studies

As indicated in the Materials and Experimental Work, the Laboratory study consisted of forging 4- by 4-inch pieces of the 4-inch-thick hot-rolled production plate (heat No. X14689) to 3- and 2-inch-thick plates at temperatures of 1600, 1800, 2000, and 2200 F.

Initial Homogenization. To establish a uniform initial microstructure that would not be affected by subsequent reheating, the 4-inch-thick plate samples were homogenized at 2300 F (a typical heating temperature for production rolling of slabs or for forging) for 2 hours and air-cooled prior to heating and forging. To determine the effect of this homogenization treatment, one of the homogenized samples was heat-treated, and mechanical properties were obtained for comparison with the production-treated plate. The homogenization treatment resulted in an embrittlement of the 12Ni-5Cr-3Mo steel as evidenced by the decrease in Charpy V-notch energy absorption at 0 F (Table II versus Table IV) from 25 and 19 ft-lb to 16 and 14.5 ft-lb at the surface and midthickness, respectively. This decrease in notch toughness was also accompanied by a decrease in average yield strength, 187 to 168 ksi, for the same condition of heat treatment.

Comparison of the microstructure of the hot-rolled and heat-treated material (Figure 1) with that of the homogenized material (Figure 4) shows the large increase in grain size (Figure 4A) resulting from the 2300 F homogenization treatment. Figures 4B and 4C indicate that the subsequent solution-annealing treatment had no effect on the grain size. The microstructure was similar throughout the plate thickness.

In addition, the fracture of broken Charpy V-notch impact specimens from the homogenized material was faceted (Figures 5A and C). This faceted fracture, the heavily etched grain boundaries evident in Figures 5B and D, and low energy-absorption values (16 to 14.5 ft-lb) indicate that a grain-boundary embrittlement has resulted from the homogenization treatment. The cause of this grain-boundary embrittlement was determined by taking carbon-extraction replicas from the steel and analyzing the extracted grain-boundary particles (shown in Figure 6) by electron diffraction. The electron diffraction results indicated that these particles may be TiC.

<u>Mechanical Properties of Forged Plates</u>. The homogenized 4-inch-thick plate samples were heated 100 degrees above the indicated forging temperature, air-cooled to the forging temperature, and forged to 3- and 2-inch-thick plates. After sectioning, the as-forged plates were solution-annealed at 1500 F for 1 or 4 hours, water-quenched, and aged at 900 F for 3 hours. The mechanical properties of the heat-treated 3- and 2-inch-thick forged plates are presented in Table IV.

In general, for the same aging treatment, the yield strengths shown in Table IV are lower than those of the original 4-inch-thick rolled plate. This change in aging response is probably a result of the titanium carbide precipitation that occurred during the initial high-temperature homogenization treatment. In addition, plates solution-annealed for 4 hours exhibited lower yield strengths (1 to 9 ksi lower) than plates solution-annealed for

1 hour. Forging from 4 inches to 2 inches resulted in slightly higher yield strengths (1 to 8 ksi higher) than forging from 4 inches to 3 inches, especially at the 2000 and 1800 F forging temperatures.

The notch toughness of the forged plates shown in Table IV is summarized (for plates heat-treated with a 4-hour solution anneal) in Figure 7. The results indicate that if the degree of reduction is low (4-inch-thick plate reduced to 3-inch-thick plate—about a 25% reduction in thickness), forging temperatures in the range 1800 to 2000 F produce optimum notch toughness (about 28 ft-lb Charpy V-notch energy absorption at 0 F). If the degree of reduction is high (4-inch-thick plate reduced to 2-inch-thick plate—about a 50% reduction in thickness), the notch toughness near the surface is highest (about 35 ft-lb at 0 F) when the forging is conducted at 1600 F, and the notch toughness at the midthickness is highest (about 33 ft-lb at 0 F) when the forging is conducted at 1800 F.

The lowest notch toughness was exhibited by the 4-inch-thick plate forged to 3-inch-thick plate at 1600 F (Charpy V-notch energy-absorption values at 0 F of about 16 and 24 ft-lb at the surface and midthickness, respectively); it was only slightly higher than the notch toughness exhibited by the homogenized and heat-treated 4-inch-thick plate (about 15 ft-lb at the surface and midthickness).

<u>Microstructure of Forged 3-Inch-Thick Plates</u>. For the 4-inch-thick plate forged to 3-inch-thick plate at 2000 F, the as-forged microstructure

may be compared with the forged and heat-treated microstructure at the surface and midthickness in Figure 8. Generally, these photomicrographs are representative of the 3-inch-thick plates forged at 2200, 2000, and 1800 F. The as-forged grain size at the plate surface (Figure 8A) is large compared with that at the midthickness (Figure 8B), and appears to be more distinct after the solution-annealing and aging treatment (Figure 8C). The microstructures obtained by forging at 1800 F (Figure 9) are generally similar to those obtained by forging at 2000 F (Figure 8). The major difference appears to be a slightly coarser structure at the midthickness of the plate forged at 1800 F.

Examination of the microstructure of the 3-inch-thick plate forged at 1600 F (Figure 10) indicates that the grains are generally large and heavily outlined with precipitate. Heat treatment has had little effect on the surface grain structure but has reduced the grain size and the distinctness of the grain-boundary outline at the midthickness (Figure 10D).

The fractures of broken Charpy V-notch impact specimens taken from surface material were faceted (Figure 11A), whereas those of broken Charpy V-notch specimens taken from midthickness material exhibited a shear-type fracture (Figure 11C). As observed at lower magnification in Figure 10, the prior austenite grain boundaries at the surface (Figure 11B) are continuous and heavily etched, while the grain boundaries at the midthickness are faint and discontinuous. The faceted fracture, heavily etched grain boundaries, and low energy-absorption values (16.5 ft-lb energy absorption at 0 F) indicate that the grain boundaries at the surface of the heat-treated 3-inch-thick plate forged at 1600 F are embrittled; however, the grain boundaries at the midthickness of the heat-treated plate were not severely embrittled (25.5 ft-lb). To establish the cause of the aforementioned grain-boundary embrittlement, a carbon-extraction replica was taken from the surface of the 3-inch-thick forged plate and examined with the electron microscope and electron diffraction. Figure 12 shows typical extracted grain-boundary particles that were identified as probably TiC in conjunction with an unidentified phase.

Thus, it appears that with plate reductions of about 25 percent (from 4 inches to 3 inches), marked grain growth and embrittlement can occur, particularly at the surface of 12Ni-5Cr-3Mo steel plate forged at 1600 F. Although a uniform and fine-grained structure was not obtained from surface to midthickness of the plate at any forging temperature from 2200 to 1600 F, optimum mechanical properties and microstructure appear to result from forging in the range 1800 to 2000 F.

Microstructure of Forged 2-Inch-Thick Plates. Figures 13, 14, and 15 show the longitudinal microstructure of 4-inch-thick plate forged to 2-inch-thick plate at 2000, 1800, and 1600 F, respectively. Generally, the microstructures of the 2-inch-thick plate forged at 2000 F are representative of those observed in 2-inch-thick plate forged at 2200 F. When plates were forged at 2000 F, the grains were equiaxed both at the surface and at the midthickness, and the grains at the surface were larger (Figure 13A) than at the midthickness (Figure 13B). When plates were forged at 1800 F, the grains at the surface (Figures 14A and C) were similar in size and appearance to those at the surface of plates forged at 2000 F. However, at the midthickness the structure obtained by forging at 1800 F is quite different from that obtained at 2000 F. Rather large, elongated grains are present in the as-forged material (Figure 14B); following heat treatment (Figure 14D), the structure has a partially recrystallized appearance with evidence of directionality remaining. When the forging temperature was decreased to 1600 F, the as-forged grain size at the midthickness (Figure 15B) was larger and more equiaxed than that observed at the midthickness of the plate forged at 1800 F, and the structure was similar in appearance to that at the plate surface (Figure 15A). However, after the plate was heat-treated, the structure at the midthickness (Figure 15D) had a partially recrystallized appearance and the structure at the plate surface remained coarse (Figure 15C).

Forging to 2-inch-thick plate at 1600 F produced the highest notch toughness of any forging condition. Although the microstructure at the surface and midthickness was markedly different after heat treatment of the plate, the notch toughness at the surface and midthickness was similar--37 and 35 ft-lb Charpy V-notch energy absorption at 0 F, respectively. Examination of the fracture surfaces of the tested Charpy V-notch impact specimens (Figure 16A and C) and of the microstructure (Figure 16B and D) at the surface and midthickness of the plate forged at 1600 F indicated that the no grain-boundary embrittlement was present.

On the basis of the data obtained in this Laboratory study, it is apparent that in forging operations where very heavy reductions are not possible (more than 50%) a minimum forging temperature of about 1800 F must be maintained. If however heavy reductions are possible, a forging temperature below 1800 F can be used and some additional increase in notch toughness can be gained, particularly at the surface, as the temperature is decreased to 1600 F. Generally, it was also noted that heavy reduction (50%) resulted in better toughness levels and more uniform structures from surface to midthickness of the 12Ni-5Cr-3Mo steel.

The influence of the embrittlement produced by the initial homogenizing treatment at 2300 F cannot be readily assessed. The metallographic studies of the as-forged plates indicate that the starting microstructure is quite effectively destroyed by the forging operation and replaced by either a new, highly distorted or a completely recrystallized structure. Thus, the initial structure may have little effect on the properties of the forged plate. However, because the embrittlement obtained by homogenizing at 2300 F may be associated with the very coarse grain size developed at this high temperature, there may be merit to the use of lower temperatures for heating prior to forging.

Second Production Forging of Heavy Plate

On the basis of the evaluation of production-rolled and forged plates and the Laboratory study of the effect of forging variables, a second forged 4-inch-thick plate was produced according to the following instructions: (1) the maximum heating temperature should be 2150 F, (2) the number of drafts should be kept to a minimum, and (3) the forging should be conducted in the temperature range 2000 to 1800 F. In compliance with these instructions, a 4-inch-thick plate of 12Ni-5Cr-3Mo steel was forged from a 10-3/4-inch-thick slab (heat No. X15604) in three drafts. The slab was heated to 1965 F, and the surface temperature at the completion of forging was 1700 F (optical pyrometer). It was estimated that internal temperatures at the completion of forging were about 1800 F. The tensile and impact properties of the heat-treated 4-inch-thick plate are presented in Table V.

As with the first forged plate, the tensile and impact properties varied from surface to midthickness. The strength was highest at the surface and the toughness was lowest at the quarter-thickness. However, the level of notch toughness in the second forged plate was higher than that in the first, and the difference between the notch toughness of specimens in the longitudinal and transverse directions in the second forging was less than in the first forging.

Figure 17 shows the microstructure of the forged and heat-treated (solution-annealed at 1500 F and aged at 900 F) 4-inch-thick plate at the surface, quarter-thickness, and midthickness. The surface and quarter-thickness (Figure 17A and B, respectively) exhibited elongated grain structures, while the midthickness (Figure 17C) exhibited an extremely fine equiaxed grain structure. The grain size throughout the plate was significantly finer than the grain size found in either the hot-rolled (Figure 1) or forged (Figure 3) 4-inch-thick plate of the initial study.

The yield-strength—notch-toughness relation for the three production 4-inch-thick plates evaluated in this report is shown in Figure 18. The notch toughness of the final forged plate was superior to that of either the initial rolled or forged plates, and the variation in toughness values from surface to midthickness was less. Thus it appears that improved notch toughness can be achieved in heavy plates of 12Ni-5Cr-3Mo steel if the plates are forged and if control is exercised during the forging operation. Conditions that appear to be important to the production of forged heavy sections are heavy drafts, low slab heating temperatures (2150 F maximum), and 2000 to 1800 F forging temperatures, unless final reductions in excess of 50 percent are possible.

Summary

In a study to produce a 4-inch-thick plate of 12Ni-5Cr-3Mo steel with acceptable properties for hull applications, an evaluation was made of hot-rolled and of forged 4-inch-thick production plates. In conjunction with these evaluations, Laboratory studies were made of the effect of forging temperature and degree of reduction on the mechanical properties and microstructure of 12Ni-5Cr-3Mo steel. The results indicated that superior notch toughness can be achieved in forged heavy sections if control is exercised during the forging operation. Specifically, initial evaluations of hot-rolled and forged 4-inch-thick plates showed that:

1. Hot-rolled 4-inch-thick plate of 12Ni-5Cr-3Mo steel had markedly poorer notch toughness than 1/2-inch-thick plate, particularly at the midthickness.

2. Uncontrolled forging of 4-inch-thick plates (light drafts and low finishing temperature) resulted in improved notch toughness at the midthickness but did not markedly raise the toughness at the surface and quarter-thickness over that obtained in the rolled plate.

3. The 12Ni-5Cr-3Mo steel is susceptible to an unusual grain coarsening when subjected to a critical amount of work and then heated to 1500 F.

Laboratory studies of the effect of forging temperature and degree of reduction showed that:

1. Homogenization of the starting material at 2300 F produced a coarse-grained microstructure and grain boundary embrittlement.

2. To achieve optimum notch toughness in forging operations where heavy drafts (about 50% reduction) are not possible, a forging temperature of 1800 to 2000 F is advisable.

3. If heavy drafts are possible, forging temperatures below 1800 F can result in some increase in notch toughness over that obtained at forging temperatures of 1800 F to 2000 F.

4. Generally, for all forging temperatures in the range of 2300 to 1600 F, heavy drafts (50% reduction) resulted in better notch-toughness levels than light drafts (25% reduction).

Production and evaluation of a second forged plate showed that:

1. Improved notch toughness can be achieved in forged heavy sections (4-inch-thick plates) if control is exercised during the forging operation. The important controls appear to be (a) use of low reheating temperatures, (b) use of heavy drafts, and (c) forging in the temperature range 1800 to 2000 F.

2. A forged 4-inch-thick plate produced under the aforementioned controlled conditions exhibited notch toughness of 27 to 37 ft-lb energy absorption at 80 F at a yield strength of about 184 ksi.

References

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3. D. S. Dabkowski, and L. F. Porter, "The Effect of Vacuum-Consumable Electrode Remelting on the Properties of 12Ni-5Cr-3Mo Steel", Applied Research Laboratory Report, Project No. 40.018-002(21), July 1, 1964.

Table I

Chemical Composition of Steels Investigated—Percent
(Check Analysis)

Heat No.	C	Mn	P	S	Si	Ni	Cr	Mo	Ti	Al+	B	Zr	N++	O
X14689	0.023	0.088	0.004	0.008	0.094	12.10	5.21	2.86	0.24	0.38	0.0037	<0.01	0.009	ND+++
X15544	0.018	0.046	0.005	0.009	0.073	11.90	4.87	3.27	0.48	0.35	0.0022	<0.01	0.004	0.001
X15604	0.031	0.028	0.007	0.009	0.083	12.10	4.68	3.07	0.35	0.33	0.0020	<0.01	0.009	0.001

+Acid soluble.
++Kjeldahl determination.
+++ND means not determined.

Table II

Mechanical Properties of Rolled and Heat-Treated 1/2- and 4-Inch-Thick Plates of 12Ni-5Cr-3Mo Steel (Heat No. X14689)

Plate Thickness, inches	Specimen Location	Specimen Orientation	Yield Strength (0.2% Offset), ksi	Tensile Strength, ksi	Elongation in 1 Inch, %	Reduction of Area, %	Charpy V-Notch Energy Absorption, ft-lb		
							+80 F	0 F	-80 F
1/2	Midthickness	Longitudinal	190	193	13.5	61.3	45	—	41
		Transverse	195	198	13.5	61.6	38	—	34
4	Surface	Longitudinal	189	192	13.5	55.6	26	25	18
		Transverse	185	191	13.0	53.5	26	24	18
	Quarter-thickness	Longitudinal	187	193	13.0	49.4	22	18	13
		Transverse	187	193	13.0	55.2	23	19	15
	Midthickness	Longitudinal	185	191	12.0	53.1	21	19	13
		Transverse	185	191	13.5	56.5	22	19	15

NOTE: All specimens were machined from heat-treated plate material solution-annealed at 1500 F for 1 hour per inch of plate thickness, aged at 900 F for 3 hours, and water-quenched. The results are the average of duplicate 0.252-inch-diameter tension tests and duplicate standard Charpy V-notch impact specimens.

Table III

Mechanical Properties of Forged and Heat-Treated 4-Inch-Thick Plate of 12Ni-5Cr-3Mo Steel (Heat No. X15544)

Specimen Location	Specimen Orientation	Yield Strength (0.2% Offset), ksi	Tensile Strength, ksi	Elongation in 1 Inch, %	Reduction of Area, %	Charpy V-Notch Energy Absorption, ft-lb			
						+80 F	+32 F	0 F	-80 F
Surface	Longitudinal	194	201	12.0	50.2	23	29	—	11
	Transverse	205	212	11.5	56.0	33	30	—	13
Quarter-thickness	Longitudinal	191	202	11.0	48.4	22	21	—	14
	Transverse	199	211	10.0	40.8	27	29	—	16
Midthickness	Longitudinal	194	201	12.0	55.6	29	27	—	20

NOTE: All specimens were machined from heat-treated plate material solution-annealed at 1500 F for 4 hours, water-quenched, aged at 900 F for 3 hours, and water-quenched. The results are the average of duplicate 0.252-inch-diameter tension tests and duplicate standard Charpy V-notch impact specimens.

Table IV

Effect of Forging Temperature and Degree of Reduction on the Mechanical Properties of 12Ni-5Cr-3Mo Steel (Heat No. X14689)

Forging Temp, F	Solution Annealing at 1500 F, in hr	Specimen Location	Yield Strength (0.2% Offset), ksi	Tensile Strength, ksi	Elongation in 1 Inch, %	Reduction of Area, %	Charpy V-Notch Energy Absorption, ft-lb +80 F	0 F	-80 F
Homogenized	1	Surface	174	183	13.5	52.4	—	17	16
		Midthickness	174	183	14.5	53.5	16	17	14
Homogenized	4	Surface	169	177	10.5	39.6	—	16	—
		Midthickness	168	177	10.5	42.6	19	15	11
		4-Inch-Thick Plate Forged to 3-Inch-Thick Plate (About 25 Percent Reduction)							
2200	1	Surface	176	183	15.0	61.5	35	28	26
		Midthickness	175	183	14.0	60.0	29	27	23
	4	Surface	170	178	13.5	58.1	32	27	23
		Midthickness	169	180	15.0	59.0	27	25	24
2000	1	Surface	175	181	13.5	57.0	30	29	23
		Midthickness	175	182	15.0	60.5	34	31	26
	4	Surface	170	178	13.5	58.1	30	27	24
		Midthickness	169	180	15.0	59.0	32	31	25
1800	1	Surface	172	178	13.5	57.0	25	26	23
		Midthickness	172	179	13.5	59.5	28	28	25
	4	Surface	169	177	14.0	55.9	30	28	24
		Midthickness	169	177	12.5	60.4	33	31	24
1600	1	Surface	176	182	9.5	37.2	28	16	21
		Midthickness	177	183	13.5	54.3	22	22	18
	4	Surface	170	177	14.0	58.6	21	17	17
		Midthickness	171	178	11.0	55.8	27	26	22

(Continued)

Table IV (Continued)

Effect of Forging Temperature and Degree of Reduction on the Mechanical Properties of 12Ni-5Cr-3Mo Steel (Heat No. X14689)

Forging Temp, F	Solution Annealing at 1500 F, in hr	Specimen Location	Yield Strength (0.2% Offset), ksi	Tensile Strength, ksi	Elongation in 1 Inch, %	Reduction of Area, %	Charpy V-Notch Energy Absorption, ft-lb		
							+80 F	0 F	-80 F
4-Inch-Thick Plate Forged to 2-Inch-Thick Plate (About 50 Percent Reduction)									
2200	1	Surface	176	182	16.0	61.6	38	31	26
		Midthickness	175	183	15.0	58.6	33	26	24
	4	Surface	172	178	15.0	60.4	—	30	20
		Midthickness	174	177	14.0	59.0	22	25	19
2000	1	Surface	177	183	15.0	60.0	30	29	25
		Midthickness	179	183	15.0	62.4	31	33	28
	4	Surface	173	179	15.0	59.0	—	28	24
		Midthickness	175	179	15.0	60.0	35	33	28
1800	1	Surface	180	184	15.0	61.6	30	31	24
		Midthickness	180	183	15.0	62.5	34	33	29
	4	Surface	172	178	14.0	63.4	—	30	27
		Midthickness	171	179	14.0	61.5	40	36	30
1600	1	Surface	176	179	14.0	56.6	36	34	28
		Midthickness	178	181	14.0	58.6	37	30	25
	4	Surface	171	178	13.0	52.1	40	37	23
		Midthickness	168	176	13.5	65.1	35	35	30

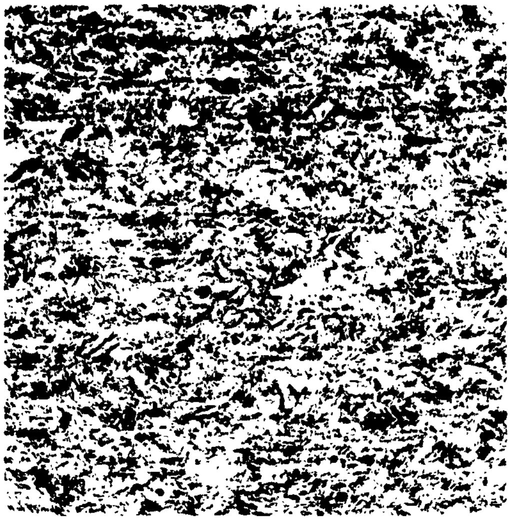
NOTE: All specimens were machined from heat-treated plate material solution-annealed at 1500 F for indicated times, water-quenched, aged at 900 F for 2 hours, and water-quenched. The results are the value of one longitudinal 0.252-inch-diameter tension-test specimen and the average of duplicate longitudinal standard Charpy V-notch impact specimens.

Table V

Mechanical Properties of Forged and Heat-Treated 4-Inch-Thick Plate of 12Ni-5Cr-3Mo Steel (Heat No. X15604)

Specimen Location	Specimen Orientation	Yield Strength (0.2% Offset), ksi	Tensile Strength, ksi	Elongation in 1 Inch, %	Reduction of Area, %	Charpy V-Notch Energy Absorption, ft-lb: +80 F	+32 F	-80 F
Surface	Longitudinal	189	193	14.0	55.1	33	31	27
	Transverse	198	201	13.0	54.6	37	34	26
Quarter-thickness	Longitudinal	176	185	14.0	48.1	30	30	24
	Transverse	181	191	13.5	49.1	27	27	20
Midthickness	Longitudinal	177	187	14.0	51.7	31	28	21

NOTE: All specimens were machined from heat-treated plate material solution-annealed at 1500 F for 4 hours, water-quenched, aged at 900 F for 3 hours, and water-quenched. The results are the average of duplicate longitudinal 0.252-inch-diameter tension tests and duplicate longitudinal standard Charpy V-notch impact specimens.



A. Midthickness of 1/2-inch-thick plate.

B. Surface of 4-inch-thick plate.

C. Quarter-thickness of 4-inch-thick plate.

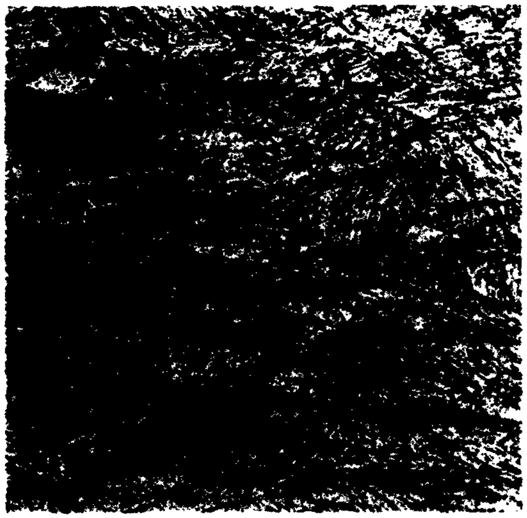
D. Midthickness of 4-inch-thick plate.

Figure 1. Longitudinal microstructure at various locations in heat-treated (solution-annealed and aged) rolled plates of 12Ni-5Cr-3Mo steel (heat No. X14689). Ferric chloride etch. X100.

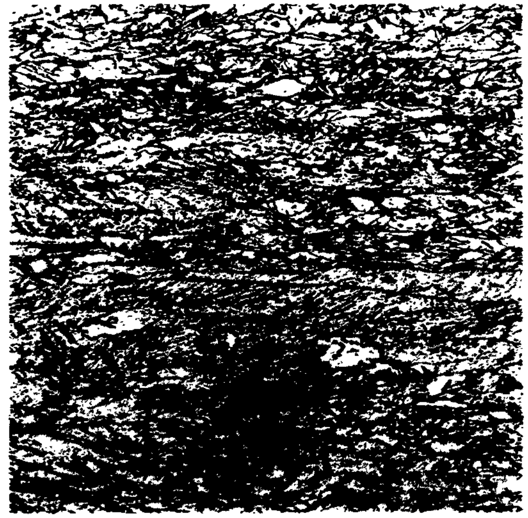
2-8999B-1
2-9003B-1
2-9004B-1
2-9005B-1

(40.018-002)(25)

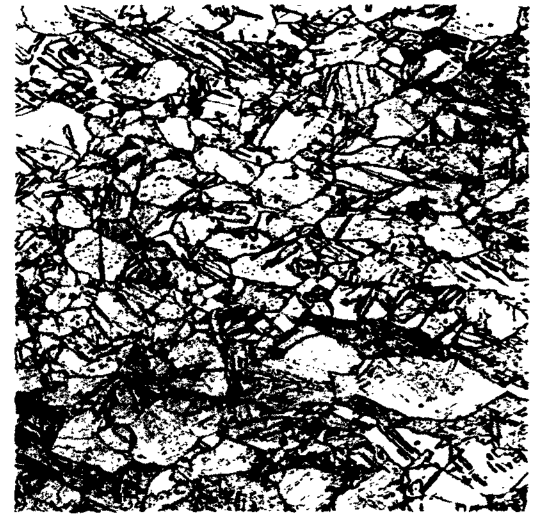
Figure 1A, B, C, D



A. Surface.



B. Quarter-thickness.



C. Midthickness.

Figure 2. Longitudinal microstructure at various locations in as-forged 4-inch-thick forged plate of 12Ni-5Cr-3Mo steel (heat No. X15544). Ferric chloride etch. X100.

18-294A-1
18-294A-2
18-294A-3

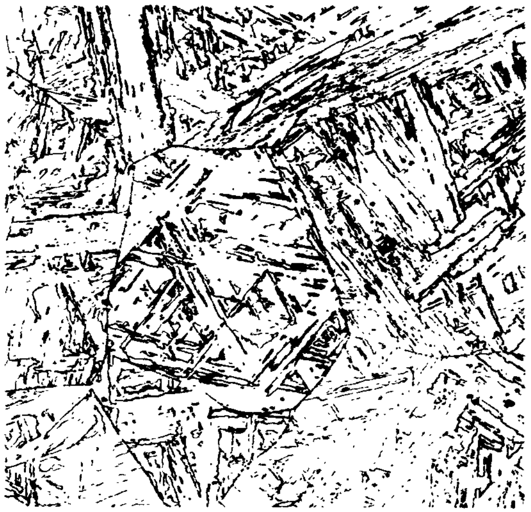
A. Surface. B. Quarter-thickness. C. Midthickness.

Figure 3. Longitudinal microstructure at various locations in heat-treated (solution-annealed and aged) 4-inch-thick forged plate of 12Ni-5Cr-3Mo steel (heat No. X15544). Ferric chloride etch. X100.

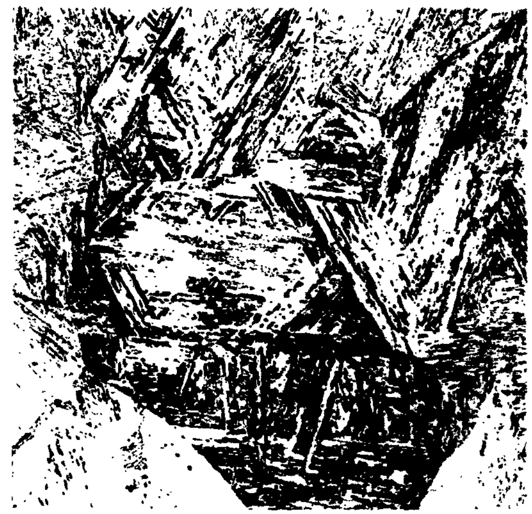
18-295A-1
18-295A-2
18-295A-3

(40.018-002)(25)

Figure 3A, B, C



A. As-homogenized at 2300 F for 2 hours and air-cooled.



B. As-homogenized and solution-annealed at 1500 F for 1 hour and water-quenched.

C. As-homogenized and solution-annealed at 1500 F for 4 hours and water-quenched.

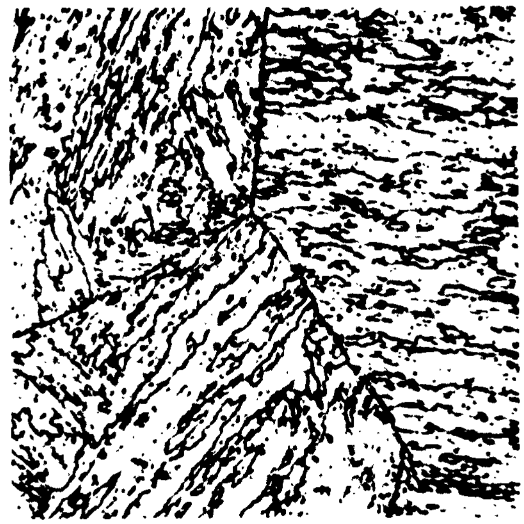
Figure 4. Longitudinal microstructure of 4-inch-thick plate of 12Ni-5Cr-3Mo steel (heat No. X14689) showing the effect of Laboratory homogenization treatment on the production-treated material. Ferric chloride etch. X100.

18-289A-1
18-290A-1
18-291A-1

(40.018-002)(25)

Figure 4A, B, C

A. Surface. X5.



B. Surface. X500.

C. Midthickness. X5.

D. Midthickness. X500.

Figure 5. Microstructure and fracture surface of Charpy V-notch impact specimens from heat-treated (solution-annealed and aged) homogenized 4-inch-thick plate of 12Ni-5Cr-3Mo steel (heat No. X14689). Ferric chloride etch.

P-4042A-8
18-274A-1
P-4042A-7
18-274A-2

(40.018-002)(25)

Figure 5A, B, C, D

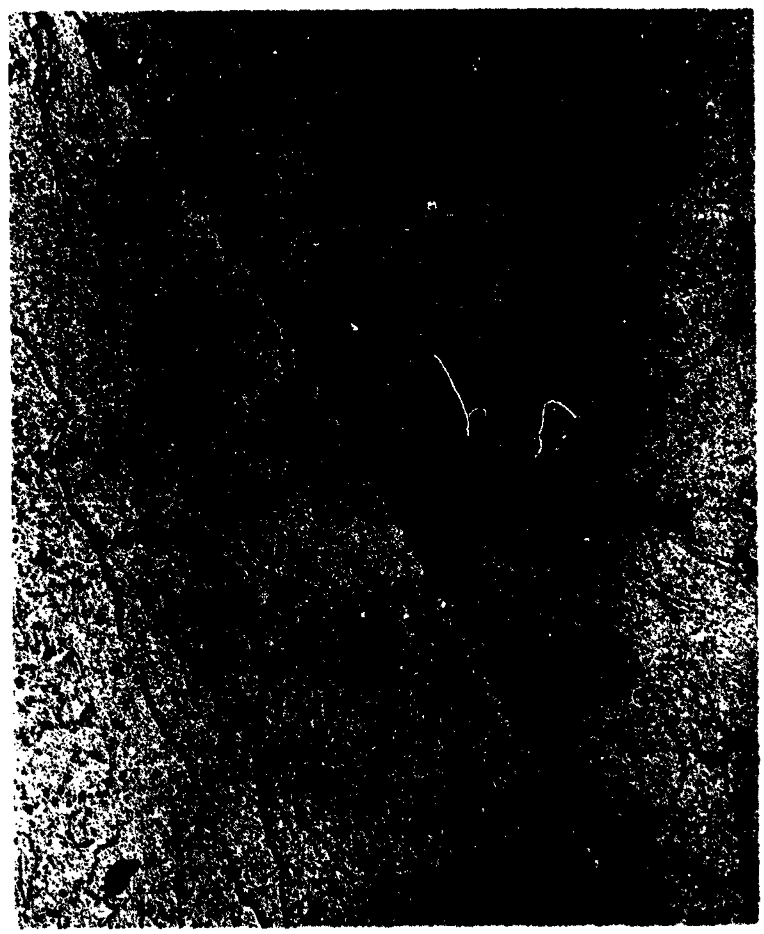
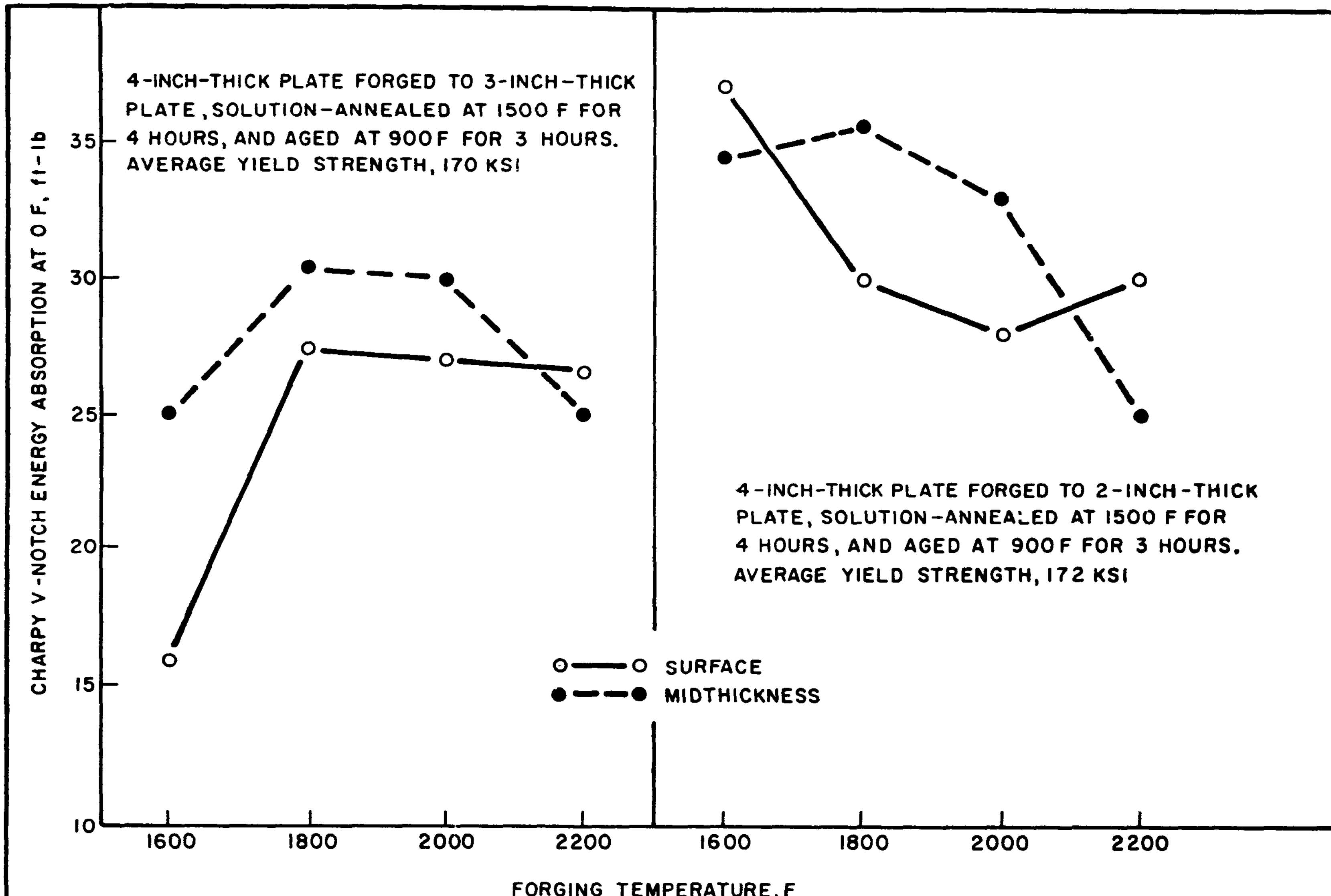


Figure 6. Electron photomicrograph of a carbon-extraction replica from the midthickness of 4-inch-thick plate of 12Ni-5Cr-3Mo steel (heat No. X14689) homogenized at 2300 F for 2 hours, air-cooled, solution-annealed at 1500 F for 4 hours, and aged. X8000.

2G-18242 REV. 1063



THE EFFECT OF FORGING TEMPERATURE AND SPECIMEN LOCATION IN PLATE ON THE CHARPY V-NOTCH IMPACT ENERGY ABSORPTION OF 12 Ni – 5 Cr – 3 Mo STEEL (HEAT NO. X14689)

DRAWN BY G.A.Z.	CHK D BY D.S.D.	APPROVED BY J.H.G.	UNITED STATES STEEL CORPORATION APPLIED RESEARCH PITTSBURGH, PA.	FIGURE NO. 7
DRAWING No ARL 18-459		PROJECT No 40.018-002 (25) DATE 11-5-64		

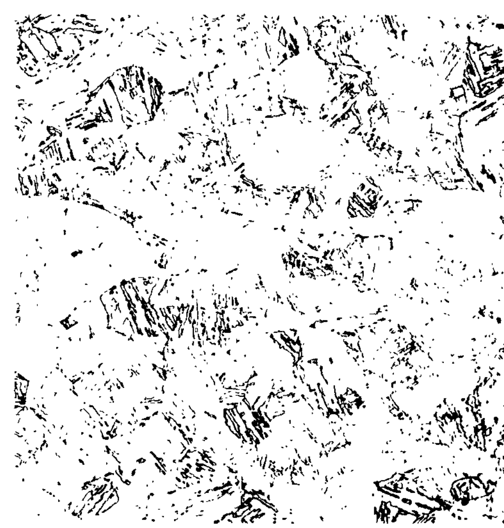
1025 Clearprint Pitt Photo Litho Co., Inc. Pgh., Pa.

A. Surface.

B. Midthickness.

Four-inch-thick plate forged to 3-inch-thick plate at 2000 F.

C. Surface.



D. Midthickness.

Four-inch-thick plate forged to 3-inch-thick plate at 2000 F, solution-annealed at 1500 F for 4 hours, and aged at 900 F.

Figure 8. Longitudinal microstructure of 3-inch-thick plate of 12Ni-5Cr-3Mo steel (heat No. X14689) in the as-forged and as-forged and heat-treated condition. Ferric chloride etch. X100.

18-275A-1
18-275A-2
18-276A-1
18-276A-2

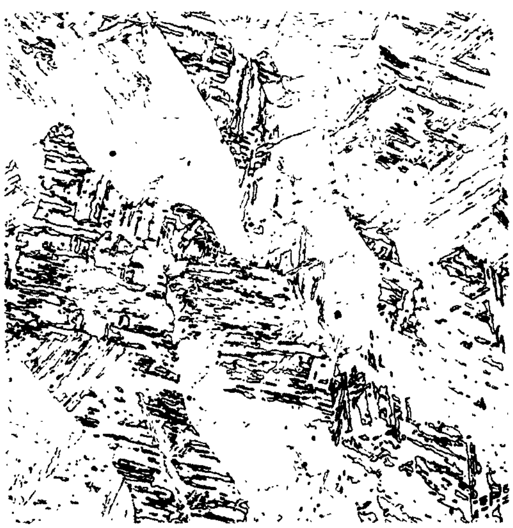
(40.018-002)(25)

Figure 8A, B, C, D

A. Surface.

B. Midthickness.

Four-inch-thick plate forged to 3-inch-thick plate at 1800 F.



C. Surface.

D. Midthickness.

Four-inch-thick plate forged to 3-inch-thick plate at 1800 F, solution-annealed at 1500 F for 4 hours, and aged at 900 F.

Figure 9. Longitudinal microstructure of 3-inch-thick plate of 12Ni-5Cr-3Mo steel (heat No. X14689) in the as-forged and as-forged and heat-treated condition. Ferric chloride etch. X100.

18-277A-1
18-277A-2
18-278A-1
18-278A-2

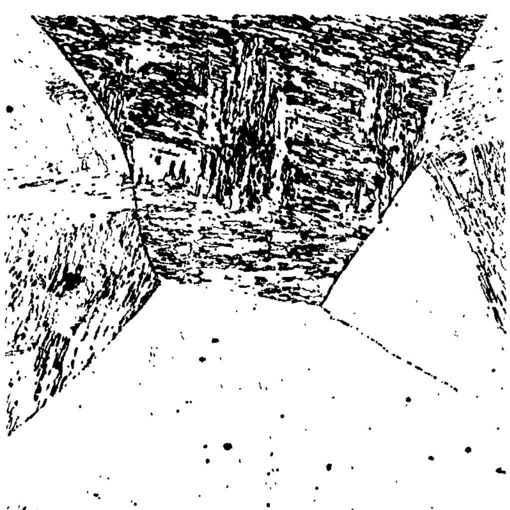
(40.018-002)(25)

Figure 9A, B, C, D

A. Surface.

B. Midthickness.

Four-inch-thick plate forged to 3-inch-thick plate at 1600 F.



C. Surface.

D. Midthickness.

Four-inch-thick plate forged to 3-inch-thick plate at 1600 F, solution-annealed at 1500 F for 4 hours, and aged at 900 F.

Figure 10. Longitudinal microstructure of 3-inch-thick plate of 12Ni-5Cr-3Mo steel (heat No. X14689) in the as-forged and as-forged and heat-treated condition. Ferric chloride etch. X100

18-279A-1
18-279A-2
18-280A-1
18-280A-2

A. Surface. X5.

B. Surface. X500.

C. Midthickness. X5.

D. Midthickness. X500.

Figure 11. Microstructure and fracture surface of Charpy V-notch impact specimens of heat-treated (solution-annealed and aged) 3-inch-thick plate of 12Ni-5Cr-3Mo steel (heat No. X14689) forged from 4 inches to 3 inches thick at 1600 F. Ferric chloride etch.

P-4042A-6
18-281A-1
P-4042A-5
18-281A-2

(40.018-002)(25)

Figure 11A, B, C, D

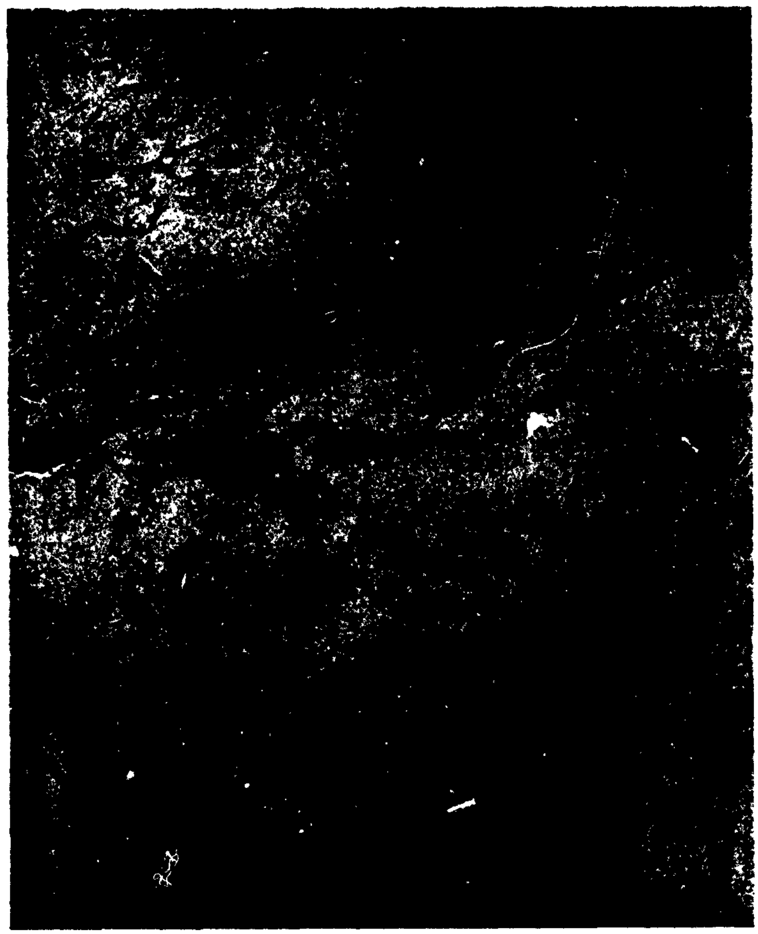


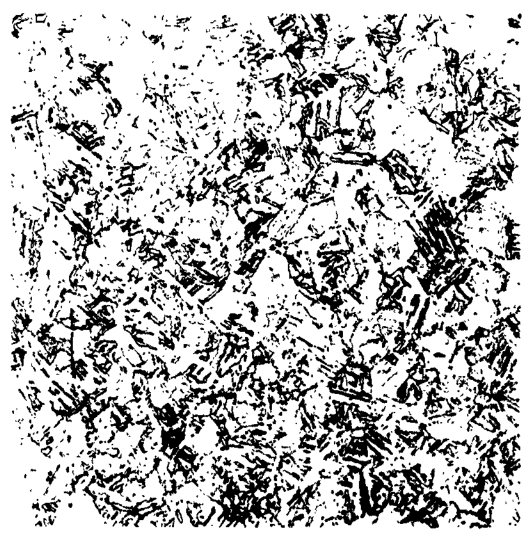
Figure 12. Electron photomicrograph of a carbon-extraction replica near the surface of heat-treated (solution-annealed and aged) 3-inch-thick plate of 12Ni-5Cr-3Mo steel (heat No. X14689) forged from 4 inches to 3 inches thick at 1600 F. Ferric chloride etch. X8000.

A. Surface.

B. Midthickness.

Four-inch-thick plate forged to 2-inch-thick plate at 2000 F.

C. Surface.



D. Midthickness.

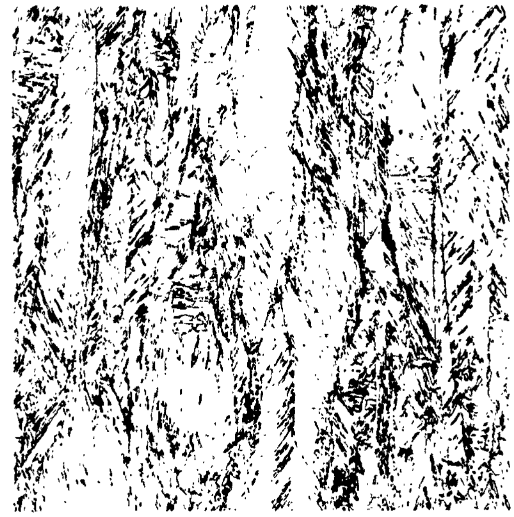
Four-inch-thick plate forged to 2-inch-thick plate at 2000 F, solution-annealed at 1500 F for 4 hours, and aged at 900 F.

Figure 13. Longitudinal microstructure of 2-inch-thick plate of 12Ni-5Cr-3Mo steel (heat No. X14689) in the as-forged and as-forged and heat-treated condition. Ferric chloride etch. X100.

18-282A-1
18-282A-2
18-283A-1
18-283A-2

(40.018-002)(25) Figure 13A, B, C, D

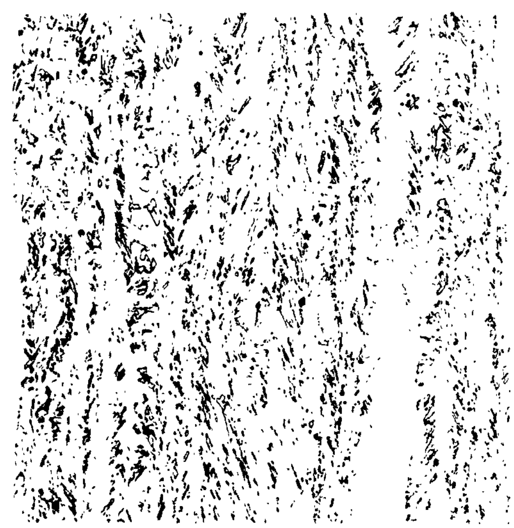
A. Surface.



B. Midthickness.

Four-inch-thick plate forged to 2-inch-thick plate at 1800 F.

C. Surface.

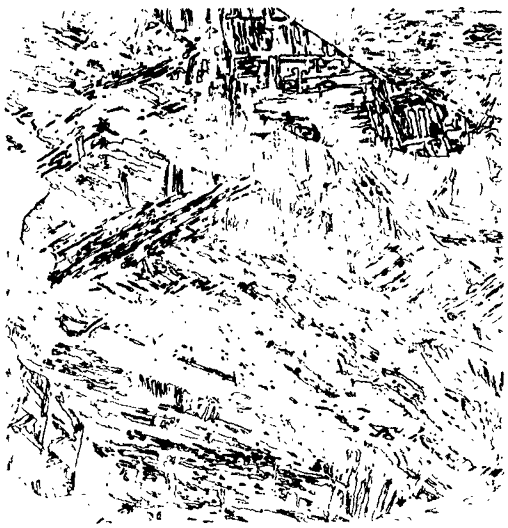


D. Midthickness.

Four-inch-thick plate forged to 2-inch-thick plate at 1800 F, solution-annealed at 1500 F for 4 hours, and aged at 900 F.

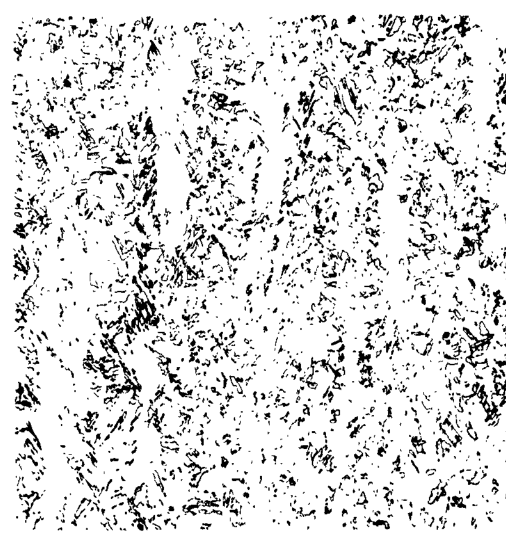
Figure 14. Longitudinal microstructure of 2-inch-thick plate of 12Ni-5Cr-3Mo steel (heat No. X14689) in the as-forged and as-forged and heat-treated condition. Ferric chloride etch. X100.

18-284A-1
18-284A-2
18-285A-1
18-285A-2



A. Surface. B. Midthickness.

Four-inch-thick plate forged to 2-inch-thick plate at 1600 F.



C. Surface. D. Midthickness.

Four-inch-thick plate forged to 2-inch-thick plate at 1600 F, solution-annealed at 1500 F for 4 hours, and aged at 900 F.

Figure 15. Longitudinal microstructure of 2-inch-thick plate of 12Ni-5Cr-3Mo steel (heat No. X14689) in the as-forged and as-forged and heat-treated condition. Ferric chloride etch. X100.

18-286A-1
18-286A-2
18-287A-1
18-287A-2

(40.018-002)(25) Figure 15A, B, C, D

A. Surface. X5.

B. Surface. X500.

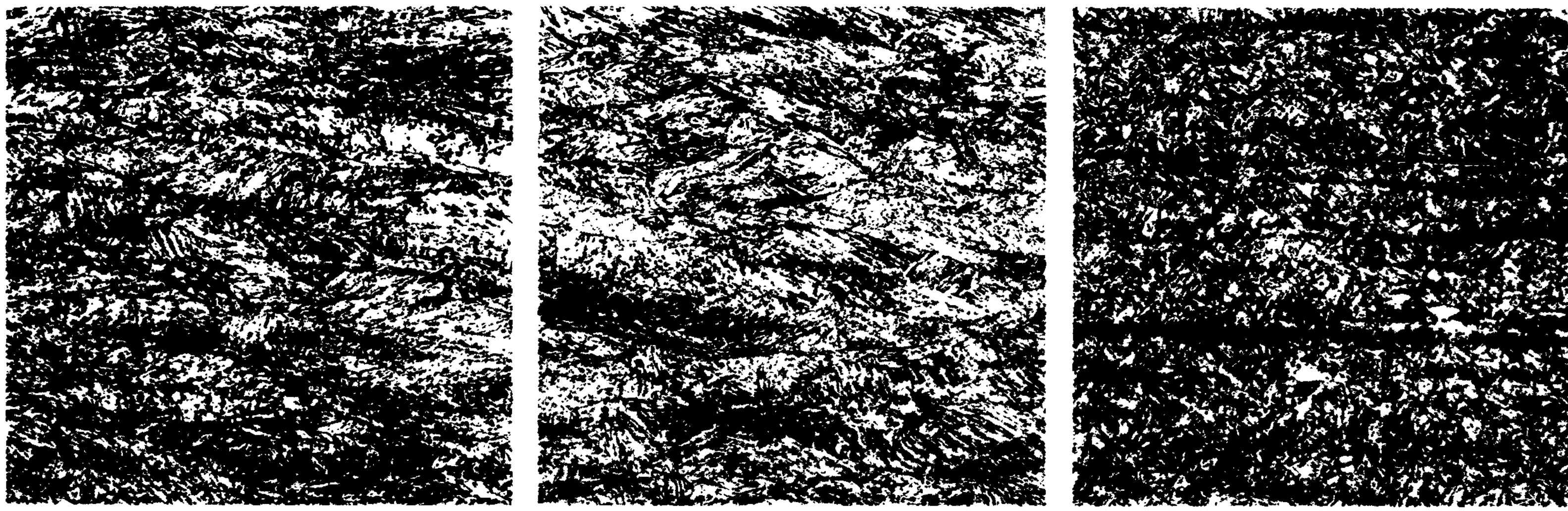
C. Midthickness. X5.

D. Midthickness. X500.

Figure 16. Microstructure and fracture surface of Charpy V-notch impact specimens of heat-treated (solution-annealed and aged) 2-inch-thick forged plate of 12Ni-5Cr-3Mo steel (heat No. X14689) forged from 4 inches to 2 inches thick at 1600 F. Ferric chloride etch.

P-4042A-2
18-288A-1
P-4042A-5
18-288A-4

(40.018-002)(25) Figure 16A, B, C, D

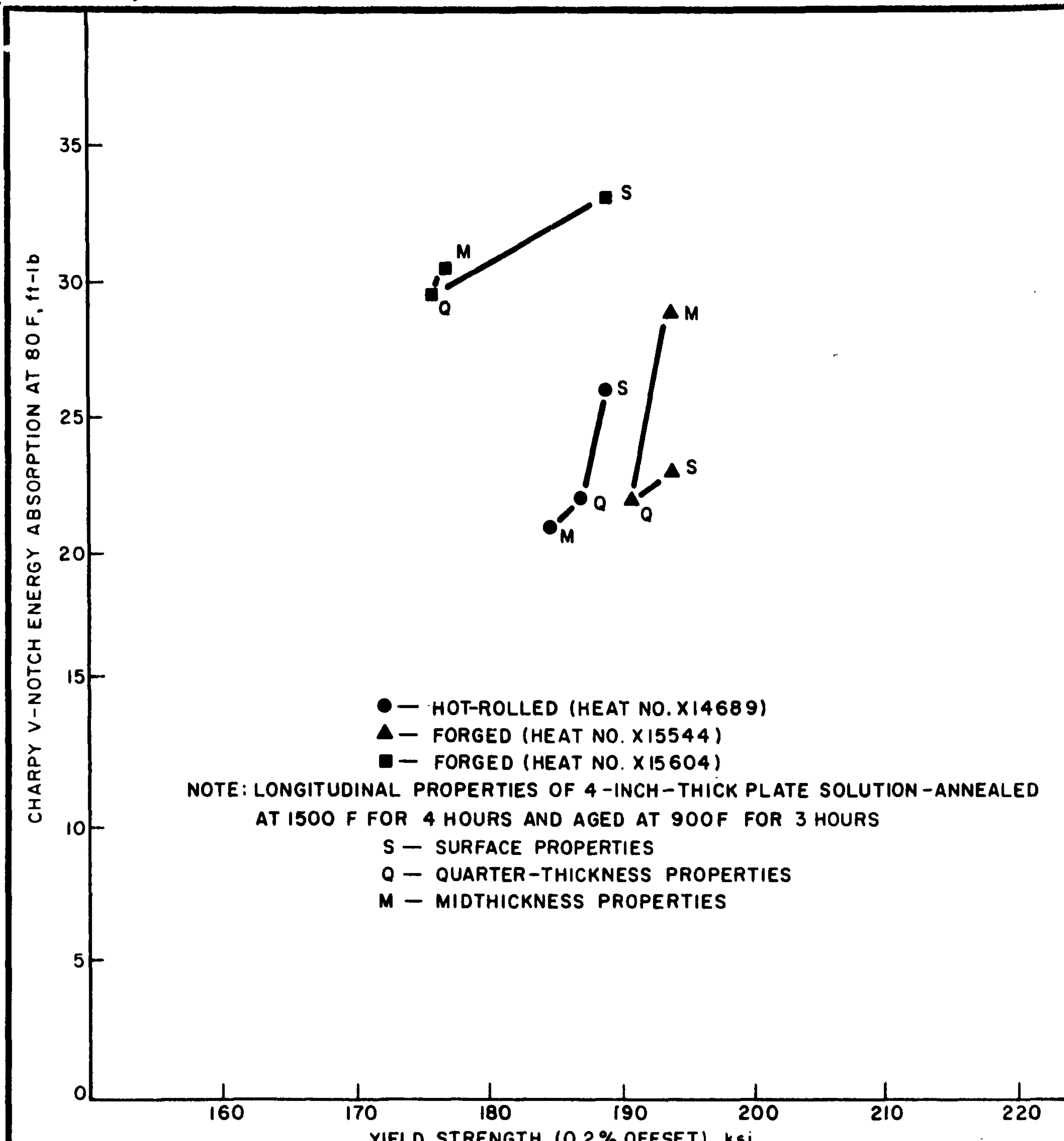


A. Surface. B. Quarter-thickness. C. Midthickness.

Figure 17. Longitudinal microstructure at various locations in heat-treated (solution-annealed and aged) 4-inch-thick forged plate of 12Ni-5Cr-3Mo steel (heat No. X15604). Ferric chloride etch. X100.

18-152A-1
18-153A-1
18-154A-1

G-18242 REV. 1063



YIELD-STRENGTH—NOTCH-TOUGHNESS RELATION OF 4-INCH-THICK PRODUCTION PLATES IN THE HEAT-TREATED CONDITION

DRAWN BY G.A.Z.	CHK'D BY D.S.D.	APPROVED BY J.H.G.	UNITED STATES STEEL CORPORATION	FIGURE NO. 18
DRAWING No. ARL 18-460		PROJECT No. 40.018-002 (25) DATE 11-5-64	APPLIED RESEARCH PITTSBURGH, PA.	

ATLAS LITHO CO PGH PA 1028 CLEARPRINT